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The Ljungström In Situ- Method for Shale Oil Recovery.

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Abstract.

The in situ-method for shale oil recovery consists in heating the shale electrically, without mining it. The method was invented by F. Ljungström in 1940. A thorough research work was made. The method was treated methematically, chemically, physically and was found to be workable. The special construction and de... problems were studied in field tests in pilot plant. In 1944 the first full-scale plant was erected by the Swedish Shale Oil Co. at Norrtorp.

The shale is heated by about 2000 electrical elements, arranged in a hexagonal hole pattern, covering a part of the field. The final temperature of the shale is 400°C, which is reached after about five months' heating. Before the heating the ground water in the shale is pumped away.

The shale is covered with a gas-tight cap rock of limestone, which prevents leakage of the vapors upwards. The oil vapors and gases are generated under a superpressure, high enough to force the products up through the vapor wells in the centres of the hexagones, through tubings, condensers, washtowers and to the sulphur recovery plant without fans.

Successively as the heating of one part of the rock is finished, a new part is heated. Thus a gigantic heat wave proceeds through the field with a velocity of 140 meters per year. A good deal of the equipment is therefore movable to follow the "heat front".

A specially designed, effective, air-cooled condensor type is used.

The products are of high quality. The crude oil is yellow-green and has a high gasolinecontent (about 52 percents). The gasoline is highly saturated and easily refined.

The gas contains about 25 percents of H_2S, which is recovered as elemental sulphur of highest quality in an Alkazid-Claus-plant. The purified gas has a remarkably high net calorific value, 8300 kcals/m^3. It is used for bottled-gas recovery and as a fuel. Certain amounts of ammonia are obtained from the pyrolysis water.

The production per sq.meter of the field area is:
oil, 1025 liter, desulphuretted gas 650 m^3, sulphur, 320 kg, ammonia 8 kg. The power consumption is 6.4 kWh/liter of oil. Thus the plant produces 3.19 cals pro 1.0 cal consumed. The total field effect is 20,000 kW.

The method may be further improved and completed. If part of the products are used as fuel in a steam power plant, the method may be thermally selfsupporting. The heat in the spent shale left behind may be used for vegetable growing. It may also be possible to inject air (or oxygen) in the hot spent shale and ignite it in order to recover its heat value (e.g. as producer gas).

The Ljungström method is also applicable to lignites, coal, oil sands etc.

Introduction.

Since the beginning of the second world war an important shale oil industry has grown up in Sweden. The works are located at Kvarntorp in the middle of Sweden and have been described by Schjånberg(1,2). Four different methods for the oil recovery are used, namely two retort methods, one tunnel oven method and the in situ-method. The scope of this paper is to give a description of the in situ-method. As this process is quite new and unique a special emphasis will be laid upon such problems that are specific for this method.

The method essentially consists in heating the shale underground without mining it, and was invented by Dr. Fr. Ljungström in 1940 (3). Although proposed also by other inventors, the in situ-principle has not earlier or elsewhere been brought up to a full scale plant.

History.

An essential part of the costs for shale oil recovery by retorting methods are the costs for mining and crushing the shale and for conveying it to and from the retorts. These considerations led Dr. Fredrik Ljungström to the idea of heating the shale directly in the rock, in situ. The heat might be supplied in the form of superheated steam, electricity or through combustion of a suitable gaseous fuel.

The research was started in 1941 along three parallel ways. The physical data and the chemical behaviour of the shale at heating were studied in the laboratory. The complicated problems concerning heat conduction, pressure distribution and flow of vapors in the shale layers were studied theoretically. The technical problems, such as construction of the heating elements, choice of materials etc. were studied thoroughly in field tests.

The laboratory experiments showed that the physical conditions for the method are fulfilled. The shale is laminated and the oil vapors can flow through the shale in the openings between the layers. The heat conductivity is not very high (λ = 0.45 kcals/m^2,h,^{o}C/m, perpendicular, λ = 1.80 kcals/m^2,h,^{o}C/m, parallel to the bed plane), which of course is unadvantageous to the heating of the shale, but advantageous in preventing heat losses to the surroundings. The mean specific heat between 0 and 400^{o}C is about 0.33 kcals/kg,^{o}C. (Fig. 1.) (These determinations were made by Widell (4).

Th experiments on the chemical behaviour of the shale revealed the following important facts:

a) The temperature, at which the pyrolysis occurs, is lower, the slower the temperature is raised. At those rates, which are possible in the Lj-plant (cf. below), 400°C is the most suitable end-temperature.

b) The quantitative oil yield varies with the heating rate according to the curve in fig. 2. The slow heating in the in situ-method thus is connected with a low oil yield. The Fischer oil yield is 5.5-6.0 % (by weight).

c) On the other hand the oil is richer in light (and more valuable) hydrocarbons and is more saturated (and thus easier to refine) than the retort oils. Fig. 2.

d) The formation of oil is accompanied by the production of a high-calorific, uncondensable gas and of some pyrolysis water, containing ammonia. (A detailed report of the pyrolysis research will be published later).

The mathematical treatment of the heat and substance flow problems was made by Lundholm (5). As a starting-point for the calculations it was assumed that the heat should be supplied to the shale seam through heating elements, placed in bore-holes, vertically drilled in the shale and uniformly distributed over the field. A hexagonal hole pattern was chosen with the elements in the corners and the vapor outlet wells in the centres of the hexagones.

The calculations showed that there would not be a uniform distribution of temperature in the whole shale mass, according to its low heat conductivity. The temperature would be highest close to the element walls and decline rapidly in radial directions outward from the element. The higher the supplied effect, the steeper the temperature curve. An idea of the heat distribution in the shale during heating is given in figs. 3 and 4. As the element tubing material would not permit too high temperatures, it was evident that the rate of energy supply must be correlated to the maximum element temperature. The neccessity not to superheat too much of the shale over 400°C is also a matter of importance, when fixing the maximum effect, because of the cracking of the products that takes place at higher temperatures.

As the element effect was thus limited and as it was desirable that the total heating time should not be too long, it was evident that the distance between the elements must not be too large. Calculations showed 2.2 meter to be the optimum distance (in this field).

The field tests simultaneously made showed the correctness of the theoretical calculations and predictions. They also showed the existance of a number of important technical problems, which had to be solved before the method was workable. Different solutions were tried in these field tests. Though several heating mediums are possible, only electrical heating has hitherto been used in tests and in plants. Some examples of problems involved may be mentioned:

a) The corrosion by action of hydrogen sulphide on the iron tubings. The formation of iron sulphide occurs the more rapidly the higher the temperature. The element temperature therefore must not exceed 700°C.

b) Prevention of gas leakage. During the pyrolysis there would be a considerable superpressure of the vapors in the rock and it would thus be important that the shale is covered with a gas-tight cap rock, such as limestone.

c) In order to facilitate the heat transfer from element to shale the air trap between the tubing and the shale wall in the hole must be filled with a heat-conducting material, suitably fine-grained sand.

d) The ground water must be pumped out of the shale layers before starting the oil recovery in order not to waste electric power for water vaporization.

The field tests were performed on an increasing scale. The first tests included only six elements and two gas wells. Successively, as the main difficulties were overcome, the tests were extended to a larger area.

The field tests were completed with a pilot plant on a semi full scale. This plant was operated from 1943 to 1946 and worked out an area of about 1.6 hectares (about 4 acres) containing about 500,000 tons of shale.

The full-scale plant at Norrtorp.

After the promising tests a full-scale plant was constructed and built by the Swedish Shale Oil Co. at Norrtorp, near the retort plants at Kvarntorp.

The shale seam is here about 17 meter in thickness and the layers are a little inclined towards the south. The shale is covered with a limestone layer about 6-7 meter thick, except along the edge, where both the shale and the limestone crop out in the open air. Fig. 5. The shale for the retort methods is mined in an open cut quarry and the Ljungström field is located on the limestone-covered part of the deposit, where mining would be too expensive. The limestone serves as a gas-tighting "roof" over the shale. The retort and the in situ-methods thus complete each other very well. The by-product plants are common to both plants.

The field is rectangular with a width of 180 meter. The heating was started at one end in twenty rows of hexagones, heated simultaneously, covering an area of 11,800 sq.m. Successively, as the heating is completed in one row, a new row is started. The heated zone ("the heat front") thus moves through the rock as a gigantic heat wave, advancing at a velocity of about 140 meter pro year. A view of the field is given on fig. 6.

The plant equipment is partly stationary, partly movable. The mobile outfit consists of drilling-machines, pumps, low-voltage field transformers, cables, wooden cable covers, and the vapor line system. The stationary apparatus are: main

pipe lines, condensers, water separators, washing tower, tankage, meters and pumps, further a high-voltage transformer station, a switchboard station and an auxiliary diesel engine with electric generator. Further may by mentioned facilities, such as electrical and mechanical workshops, stores, laboratory, office and canteen.

Preparation of the field.

Apart from the cutting off bushes and trees no clearing of the field surface is required.

The drilling is performed with about twenty rotary drilling machines with hard metal bore crowns.(Fig. 7.) The hole diamter is 5.6 cm. The holes are 26-28 meter deep and pass through about 2 m of soil,6-7 meter of limestone and 17 meter of oil shale.

The holes are arranged in a hexagonal pattern with en edge length of 2.2 meter (fig. 6).

Immediately after the drilling the holes are lined with iron tubings. The vapor wells are open through the oil-producing layers and are lined only through the overburden. The tubes end about one half meter above the ground surface.

The element holes are lined from bottom to top. The casings are manufactured by the steel works in their definit lengths, about 26 meters. It is, however, not possible to sink them in the holes directly. By raising the tube its upper end would namely be bent down by its own weight. For this reason there is used a special tube-sinking equipment (Fig. 8). It consists of a mast, as long as the tubes and revolving around a horisontal shaft. The tube is attached to the mast in down-position. By means of a counterweight and an electrical motor the mast is elevated to vertical position just above the hole and the tube is dropped. The elevator is movable on wheels from hole to hole andis loaded with two tubes a time.

The casing is closed in its lower end and has a diameter of 4.8 cm. Between the tube wall and the rock there is an annular space, which is filled with fine-grained sand in order to facilitate the heat transfer. The sand is suspended in water and the slurry is poured down under vibration. Thereby the sand fills up the space and the water flows away through fissures in the shale.

Inside the tube the electrical element is placed. Fig. 9. It consists of an ironchromium resistance, fastened to the bottom of the tube, which serves as return conductor for the current. Between the upper end of the resistance and the element head runs a soft-iron connection, the resistance of which is low enough not to cause any serious heat evolution in the nonproducing overburden. In order to increase the heat-emitting surface and thereby lower the element temperature, the resistance has been given the shape of a double, corrugated ribbon.

The element is inserted after the casing has been put into its place in the hole. To increase the heat transfer, the space between the element ribbons and the tube wall is filled with quartz sand which must be absolutely dry and free from iron particles and other impurities, which could cause short-circuits or flashovers.

Normally the ground water level in the field stands somewhere in the soil layer. As there are considerable amounts of water contained in the fissures and spaces in the shale it is neccessary to sink the ground water level before heating. This is performed by means of pumps, which are sunk down in two or more rows of vapor wells on a little distance from the "heat front". Fig. 10. Of course there will always be a flow of water from the surroundings towards this level, but this flow is counteracted by the high pressure of gases and vapors in the heated shale. Further some oil vapors leak out between the layers in the surroundings and are condensed. Thus a thin oily film covers the surface of the fine laminar channels in the surrounding rock. Because of the interfacial tension between oil and water, no water can penetrate those channels. On the other hand further out from the field the capillaries are waterwet and consequently no oil can leak out. Thus, as far as the <u>narrow</u> channels are concerned, the surface tension builds up an unpermeable wall around the hot shale. Of course the coarser fissures cannot be tightened in this manner.

<u>Power supply.</u>

The electric power has hitherto been supplied from a hydroelectric power station to the Lj-plant by a high-voltage line. In a transformer station the voltage is reduced from 132,000 to 22,000 volts. The power then passes via a switchboard station to eight field transformers, each supplying one eighth of the field with energy (fig. 11). The transformers are movable on rails and follow the advancing "heat front" with one week displacement between each section (fig. 6). They reduce the voltage to 152 volts. From these transformers the power is distributed to the element rows through thick copper rods, running under wooden covers (fig. 12) and from these to the individual elements through short cables (fig. 13). Three-phase current is used and each element is cut in between one phase and earth that serves as zero conductor. The total power required is 20,000 kW.

Heating. Production.

The total heating period is about five months. During the first three months the shale is preheated to about 280°C and during the remaining two months the temperature is increased to about 400°C. Oil is produced during this period, but the production also continues after the heating, during the levelling of the great temperature differences in the shale which are created around the heating elements.

During the pyrolysis the gases and oil vapors create a superpressure of about 200 mm of mercury in the rock. This pressure is large enough to transport the products up throughwells and through the collecting tube system, the condensers, washing tower, and to the sulphur recovery plant without any suction. Since a little overpressure is thus maintained in every part of the tube system, there is no risk for air inleakage through untight flanges etc. and consequently no explosion danger.

The vapors are collected in a network of tubes which can be transported and connected to new rows of vapor wells successively as the producing front advances.

The old vapor wells are closed with a threaded head. A careful control and regulation of the release of vapors from the rock is maintained by means of precision valves.

Condensers.

The mixture of oil vapors, water vapor and uncondensable gases leaves the shale at about 300°C. Of course there is a little condensation in the pipe lines, but most of their heat must be removed in some type of condenser.

In the Norrtorp plant a new form of condenser has been successfully used. It is air-cooled and has an especially large heat transfer surface. It consists of a number of thin chambers, arranged to a package, with a little distance between each chamber. The vapors pass through the chambers and air is blown by a fan through the spaces between them.

A number of parallel condensers are united to a battery and several batteries are connected in series to form the whole system (fig. 14). The volume of the vapors decreases as the condensation takes place and therefore the number of condensers in each battery is less in the cooler end of the condensing system.

After the passage through the condensers the gas still contains some C_5- and C_6- hydrocarbons, which are washed out with cooled crude oil in a washing tower.

In the pyrolysis there is formed not only oil and gas, but also some water. Further there is a certain amount of ground water left in the shale after pumping. This water is vaporized and condensed together with the oil.

From the condensers the mixture of water and oil flows to separating tanks. As the specific gravity of the oil is as low as about 0.87, there is no difficulty in the separation of the two liquids.

Further treatment of the products.

From the separators the crude oil and the gasoline saturated wash oil are pumped to the refinery, where gasoline, kerosene and fuel oil are manufactured. In a stabilizing plant also liquid propane-butane is recovered.

The pyrolysis water contains about 8 grams of NH_3 per liter, which is recovered as ammoniumsulphate.

Sulphur is recovered from the uncondensable gas in an Alkazid-Claus-plant, whereafter the gas is used as a fuel (at present for steam generating in a power plant; formerly as domestic fuel in a neighbouring town).

Analysis and yield of products.

The laboratory investigations had shown the difference between the oil from slow and from rapid pyrolysis. The same results are obtained in the plants. The oil from the Ljungström-plant is light, yellow-green (but darkens in the air) and of more saturated character than the retort oils. Of special interest is its high gasoline content. Some analysis data are collected in tables I and II.

Table I: Analysis of Lj-crude oil.

Specific gravity (at 15°C): 0,870

Gasoline content, 0-200°C: 52 % (by volume)

Table II: Analysis of gasoline fraction from Lj-crude oil.

Fraction 0-170°C:

Refractive index, n_D^{20} = 1.4328

Iodine number (Hübl)=60

Sulphur content = 0.8 %.

Aniline point=36.0°C

No wax and practically no lubricating oil fractions are present in the Lj-crude oil.

The oil is refined to gasoline, kerosene and fuel oils. From the latter fraction certain amounts of transformer oils are obtainable through a solvent extraction and hydrogenation process.

The quantitative yield is as mentioned in a previous section a little less than in more rapid methods of pyrolysis. The efficiency, relative to the Fischer assay test is about 60 %. On the other hand the higher percentual gasoline content and its better quality more than counterbalance the lower quantitative yield.

An analysis of the uncondensable gas after washing out the C_5-and C_6-hydrocarbons, is given in Table III.

Table III.

Gas analysis.

Gas	Crude	Pure (desulphuretted)
CO_2	5.0 %	6.7 %
H_2S	25.0	-
CO	0.5	0.7
O_2	0.0	0.0
N_2	2.0	2.7
H_2	18.0	24.0
C_nH_{2n}	4.0	5.3
C_nH_m	45.5	60.6
Gross heat value, kcal/m^3		9100
Net " " "		8300

Sulphur is recovered from this gas through selective washing. Also bottled gas (propane and butane) are recoverable from the gas in an amount of about 200 gram/m^3 and a full-scale plant for this purpose is under construction.

The total production pr field area unit is on an average:

Gasoline	515 liter/ sq.m
Kerosene	160 "
Fuel oil	350 "
Total oils	1025 liter
Liquid propane and butane	80 kg
Washed gas	650 m^3
Sulphur	320 kg
Ammonia	8 kg

Pro year is worked out a field area of 25,000 m^2, corresponding to about 875,000 tons of shale.

The energy consumption.

Of great interest is the power need for the Lj-plant, expressed most properly as kilowatthours per liter of oil. This energy quantity includes the heat required to raise the temperature of the shale plus the heat of reaction, plus the heat, neccessary for vaporization of the remaining water in the shale and also the heat losses to the surroundings. The first two of these terms are fixed for a certain shale (but of course depending on the shale qualities). The third is depending on the efficiency of the ground water pumping, or rather, on the rate of inflow of new ground water from the surroundings. Thus it is, as also the fourth term, mainly dependant on the length of the field edge relative to the field area, that is, the larger the field the less the heat for water vaporization and heat losses. In fig. 15 is shown the energy consumption at different plant sizes. As a measure for the latter is used the effect supplied to the field, but of course also the field area could have been taken. The points in the diagram have been obtained in the field tests and in the semi- and full scale plants. As is seen, the consumption approaches a minimum limit of about 4.9 kWh/liter. In the fullscale plant at Norrtorp the figure is 6.4 kWh/liter.

As the energy costs are of utmost importance for the economy of the Lj-method we may discuss them a little more. These 6.4 kWh do not only produce 1 liter of oil but simultaneously also 0.650 cubicmeter of a gas with as high a calorific value (net) as 8300 kcal/m^3. Further there is produced about 320 gram sulphur and about 8 gram ammonia. If all products and involved energies are converted to a common unit, e.g. calories, one obtains the following thermal balance for the Lj-plant at Norrtorp.

Table IV:

		Cals/1oo cals, totally involved
Debet.	Calorific value of the shale	92.7
	Supplied power	7.3
	Total	100.o
Credit.	Calorific value of the produced oil	13.4
	" " " " " " sulphur	1.8
	" " " " " " gas	8.1
	Condensing and cooling of the products	2.5
	Losses of heat, oil and gas to the surroundings	2.8
	Temperature heat in spent shale	3.5
	Calorific value of spent shale	67.9
		100.o

The energy balance is shown graphically in fig. 16.

If we regard the Lj-plant as a kind of conversion unit from electrical to calorific energy we may say that the supplied 7,3 units of electricity are converted to useful products (oil, gas, sulphur) with a calorific content of 23,3 units. In other words, the plant has a thermal efficiency of as much as 319 percent (if we do not consider the consumption of calories from the shale).

Economy.

The most outstanding difference between the Lj-method and the retorting methods is the absence of shale mining, crushing and conveying. Also economically this is the most important difference. While the pretreating of the shale before pyrolysis is the largest factor in the total costs for the "retort-oil", the heating is the largest cost factor in the "in situ-oil". In the Norrtorp plant the energy costs have amounted to about 50 per cent of the total costs. The relation between the different cost factors is shown in table V. This ~~diagram~~ table does not include return on spent investment. On the other hand these costs include research and experimental construction, which strictly taken, are not connected with the normal operation of the field.

Table V.

Distribution of the production costs.

Electric power	48.9 %
Consumption materials	18.0 %
Labor costs	16.5 %
Equipment(including repair)	7.6 %
Administration and research	6.0 %
Other costs(facilities etc.)	3.0 %

A panorama of the Lj-plant is shown in fig. 17.

Further development of the Ljungström method.

As mentioned above the full-scale Lj-plant was started in 1944. Of course there are still several problems which have not yet been definitely solved and where thus important improvements may be made.

A number of such problems have been taken under consideration and research work is going on. Some of these questions and the results hitherto obtained may be mentioned here. In some cases the results are of immediate actuality, whilst others are of interest when a new plant is planned.

The thermal balance diagram, fig. 16, may be taken as a starting-point for the discussion. It must, however, be noted, that it is not always permitted to "translate" the consumed power and the produced oil and gas to a common unit, e.g. calories, since these two kinds of energy are not always interchangeable in their use. There is always a great need of liquid fuels that cannot be compensated by electric power. For such reasons the oil calories are often more valuable than electrical calories.

With these remarks in mind we may discuss some of the possibilities to increase the ratio: $\frac{\text{useful products}}{\text{input energy}}$.

Because of the relatively low overall thermal efficiency of a steam power plant (about 30 %) there is at present no possibility to use part of the produced oil and gas as fuel and thus obtain enough electrical power for the Lj-plant. But if a larger Lj-plant is built, the diagram in fig. 15 shows that the net energy consumption per liter of oil will be less and thus it will be possible to build a self-supporting plant, if e.g. all the gas and part of oil is burnt in a steam power plant.

Another possible combination, which gives a higher efficiency of the whole plant, is <u>to preheat the shale</u> by means of low pressure steam from a counter pressure turbine before the electrical heating is set on.

Another interesting possibility is the use of the field as a large <u>energy accumulator</u>. (7). The pyrolysis does not start before the temperature of about 280°C is reached. If the shale in the field is heated to this temperature, no considerable oil and gas production occurs.

This fact may be used in the following way. Under periods, when plenty of cheap power is accessible, a larger field is heated up to about 280°C. Because of the low thermal conductivity of the shale, the heat can be stored in the rock for a long time (years). When a period of power or fuel shortness is coming, some additional heat must be supplied for pyrolyzing the shale. Thereby a considerably higher production is obtained than would have been possible with the actual power supply (without preheating). The advantage of this method may be expressed in different ways:

a) the surplus electrical power (in the nights, or in summer, or in rain-rich years) instead of being wasted, is accumulated.
b) the production costs for the oil can be considerably decreased, since the main part of the power need can be cheap second-grade power.
c) when the supply and demand of fuels and electrical energy are not in balance, this is a means of restoring this balance through transforming electrical energy to liquid fuels (in the field) or fuels to electrical energy (in the connected shale-gas heated steam power plant).

There are also some possibilities to increase the utilization of the terms in the lower end of the diagram (fig. 16).

The losses through oil and heat leakage can be reduced through increase of the field size as is mentioned above.

Concerning the physical heat of the spent shale (the "shale coke") there is an interesting proposal made. When the pyrolysis is finished, the temperature in the rock is about 400°C. As the heat conductivity is very low in both the shale and the surrounding minerals, the cooling of the spent shale proceeds very slowly. If all heat transport occurs through conduction in the solid materials, there will be considerable amounts of heat remaining in the heated shale also after a hundred years of cooling, according to calculations made by E. Lundholm (5). It is experimentally found, however, that the cooling will be a little more rapid, because of the inflow of ground water in the larger fissures in the shale. When the water reaches the hot shale, it vaporizes. The vapor stands under pressure and flows consequently outwards through other fissures and gives off its heat through condensation in the cooler surroundings. In this way there will be a more rapid heat flow from the field until the temperature of the spent shale has sunk to a little below 100°C. Thereafter no considerable vaporization occurs and the rapid cooling ceases. The heat transport through water vapor cannot be calculated, but it will last several years before the whole field is cooled to below 100°C.

In a field of the actual size most of the heat is transmitted uppwards to the field surface. Thus the ground has a considerably higher temperature than normally. Dr. Ljungström has proposed (3) that this surplus heat should be used for growing vegetables, flowers etc., either in the open air or preferably in green-houses. As the total available heat is about 3.10^6 kcal/sq.m. it is evident that considerable amounts of coal (or other fuels) can be saved in this manner. For comparison may be mentioned that green-houses in Sweden as an average annually consume about 1000 kcal/sq.m.

Some growing tests have been made with positive results, but no green-houses have as yet been built.

The most important energy term on the output side of fig. 16 is the calorific value of the spent shale. Fresh shale has a calorific value of about 2000 kcals/kg and spent shale has about 1500 kcals/kg. There are also som possibilities for making this energy useful. After the oil recovery one may press air in the shale through the vapor wells. Then the spent shale is ignited and burns as long as air (or oxygen) is supplied. The liberated heat may be used for different purposes:

a) for heating neighbouring, unpyrolyzed shale. In this case the electrical energy may be unneccessary for the oil recovery, apart from a little amount needed for igniting the shale at the start of the plant. This is a form of a thermally selfsupporting plant.
b) for maintaining the higher temperature in the field and thereby creating conditions for a longer lasting growing of vegetables.
c) for generating producer gas (at higher temperatures), which is collected through another similar tube system as the oil vapours, and used as a fuel. This method for recovery of low-value coal energy is, as wellknown, in use in Russia and elsewhere.

Som experiments on air injection and shale combustion have been made in the semifull scale Lj-plant at Norrtorp, when oil recovery was finished. The tests were on the whole successfull, although the presence of fissures in the seam caused some difficulties in maintaining an even combustion througnout the shale. Another experience was that the temperature that is neccessary for producer gas formation (about 900°C) probably can not be attained with air, but requires injection of oxygen or air, enriched with oxygen. The experiments are not finished, but are temporarily set aside for other problems.

<u>ield restoration.</u>

In a previous section is mentioned the possibility of using the spent shale field for greenhouses etc. If larger areas are worked up, it may perhaps not be possible to cover the whole field with such houses. As the shale is situated in a good farm district it will then be desirable to restore the field for farming purposes, successively as the front advances.

The only visible remains ofter the oil recovery are the upper ends of the element and vapor tubings, which stand up about one half meter above the ground. It is not now possible to lift the tubings out of the rock after heating because of the tightly filled sand outside the tubings and of the small, horizontal displacements which occur in the shale layers at the heating.

Methods are, however, worked out for the removing of the upper parts of the tubes. The element tubes are emptied from inner sand filling to a depth of about one meter. The tube is cut off from inside and the upper part is lifted by means of a portable winch.

The ploughs never go deeper than one half meter and therefore the tubes left behind in the rock are no obstacles for using the field as farmland.

The application of the Lj-method to other materials.

The in situ-principle is not limited to oil shale. It is also possible to apply it for carbonization of lignites and coal, where the conditions are about the same as in shale. But also bituminous sands, oil sands and other materials, which contain free oil may sometimes advantageously be treated in the same way.

In recovery of oil from sandstone through drilling and pumping only part of the oil content is recovered. To increase the yield the oil producers flood the rock with water. But even after water flooding considerable quantities of oil remain in the rock because of viscosity and surface tension phenomena. A common figure on the remaining oil after water flooding is one third of the oil originally present, but Fettke estimates that 60 percent of the total oil in the Bradford pool, Pennsylvania, will remain after the entire pool has been watered out (6).

By heating the rock according to the Lj-method it seems, however, possible to lower the viscosity and surface tension and so facilitate the flow of the oil towards the wells. This usage of the Lj-method differs from the shale oil recovery in that the oil in oil sand is not heated above its boiling point and is thus obtained in liquid, not in vapor state.

In some kinds of bituminous sands, on the other hand, the oil is not present as free oil, but as a bitumen, which cracks to oil at heating to about 200°C. Such sands are found in Canada (Athabasca). In such sands water flooding is of no effect. Mining and heating it in retorts or containers is expensive and difficult. Heating in situ therefore seems to be a suitable method for the oil recovery.

If the in-situ-method is to be used on a certain deposit (shale or sand), it must be given that special design, which is most suitable for this purpose. There are great possibilities to adjust the well pattern, the element construction, the effects, the temperatures, the drilling methods etc. to the local conditions. If for example, the material is very deeply situated, it may probably be suitable to increase the well distance in order to decrease the drilling and tubing costs and simultaneously make the heating periods longer. The method is thus very flexible to varying conditions.

Of that reason it is not possible to make any general statements about the economy of the Ljungström method. An individual estimate must be made for every special project. The most important costs are, however, always the drilling and tubing costs and the electrical power.

When considering the economy, one must also remember the very important fact that the efficiency of the method is quite dependant on the qualities of the shale (sand). All figures given in this paper refer to a shale, which has a Fischer oil content of 6 % (b.w.). Most of the supplied heat is, however, required for heating the inorganic matter in the shale to 400°C and only a little amount is consumed for conversion of the kerogen to oil and gas. If therefore the oil content of a shale is 12 % (b.w.) the method will give twice as much oil per supplied power unit as in the Norrtorp plant, or in other words, the specific power consumption will be 3.2 kWh/liter instead of 6.4 kWh/liter.

Discussion.

Although quite new the Ljungström principle has already demonstrated its possibilities. The first laboratory investigations were made in January 1941 and a little more than three years later the full scale field was started. Of course there were a lot of special problems involved, which had not earlier been met with in design and construction practice. The problems were solved and the plant has worked satisfactorily. But it may be foreseen that there will be several improvements made on the plant successively as the time permits a more thorough investigation of every special problem, revealing more adequate solutions.

Another outstanding feature of the method is its applicability on shales and other fossile fuels under varying conditions. Some designing and economic calculations recently made on foreign projects have indicated that the method may be used with sucess also on deeply situated shales and oil sands.

There are also further possibilities in the method, which are not yet used, e.g. the growing of vegetables on worked-up field, the combustion of spent shale through air injection etc.

The plant is temporarily at a stand still because of the shortage in water power in Sweden, but as soon as the Swedish Shale Oil Company's own new steam power plant, now under construction, is complete, the operation will be started again. This power plant will produce power from the surplus high pressure steam from ~~the Bergh-Kvarntorp~~ retort ovens. The two methods will thus complete each other very well.

The oil, produced by the Lj-method, is of a remarkably good quality. Part of its "refining" is made, so to say, down in the rock during the long heating.

At last may be mentioned the low requirements of operating personnel, the minimum land wasting, the low capital investments, ~~the absence of plant-destroying waste gases,~~ and the clean and dustless operation.

Literature references:

1. E. Schjånberg: Production of Shale Oil in Sweden. World Power Conference, The Hague, 1947, Section A3, no. 4.
2. E. Schjånberg: The Swedish Shale Oil Industry. United Nations Scientific Conference on the Conservation and Utilization of Resources, Fuels 3(c)/1, 30 May 1949.
3. F. Ljungström: Swedish Patents, no. 121.737 (28/1o 1940) 123.136(4/12 1941 123.137(23/2 1943), 123.138 (30/1 1945).
4. T. Widell: (The Steam Heat Institute, Stockholm), unpublished work.
5. R. Lundholm: Unpublished works.
6. Ch. Fettke: The Bradford Oil Field. (Harrisburg, Pa. 1938), p.448.
7. F. Ljungström: Swedish Patent no. 126.674 (7/1 1946).
8. F. Ljungström: Swedish Patent no. 125.712 (4/7 1946).

SVENSKA SKIFFEROLJE A.-B. Ljungströmsanläggningen	Physical data for oil shale at heating	

c = mean specific heat between 0 and t°C.
λ = heat conductivity perpendicular to bed plane.

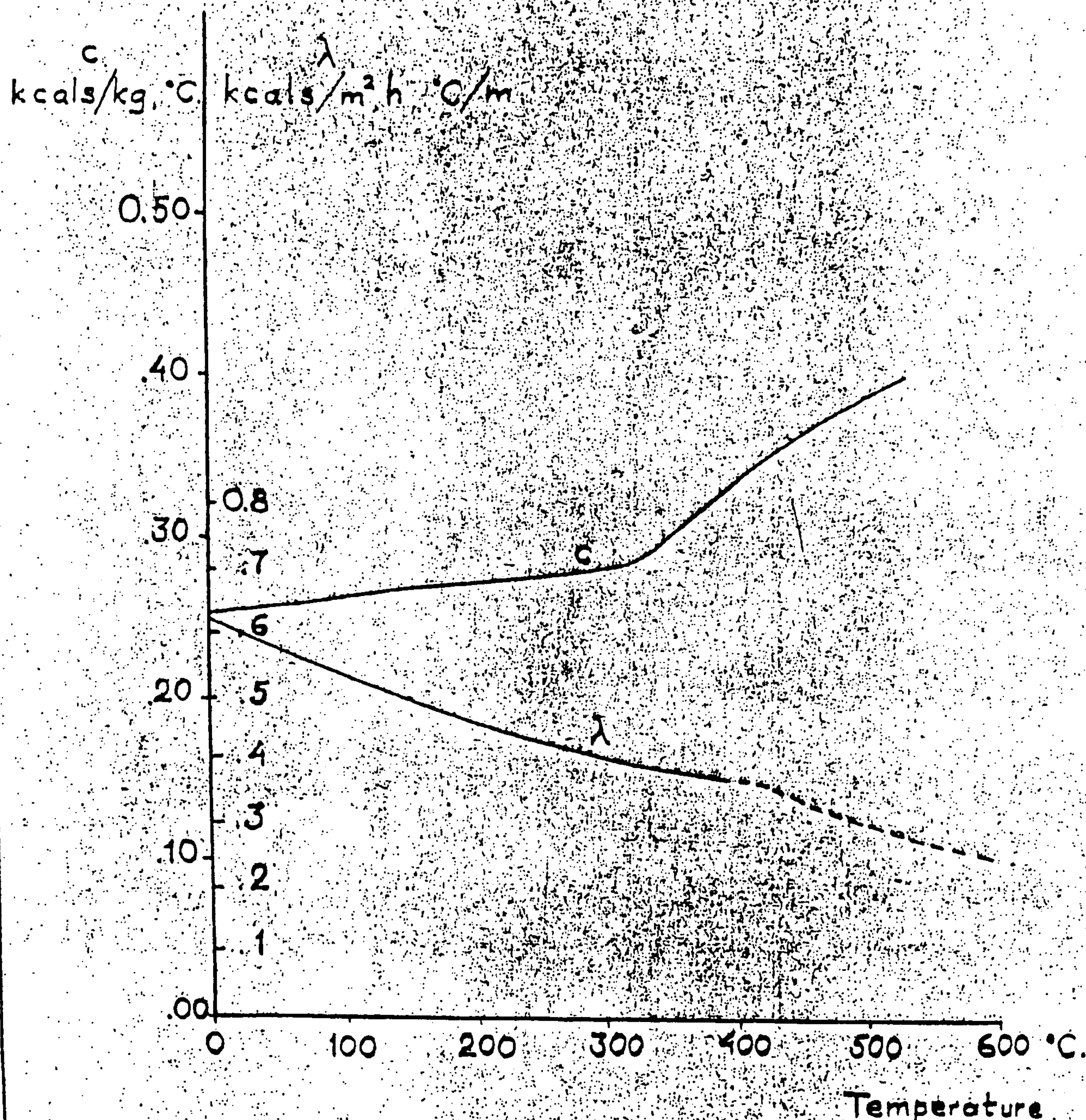


Fig.1.

SVENSKA SKIFFEROLJE A.-B. Ljungströmsanläggningen	The dependance of oil yield and oil quality on the rate of heating	

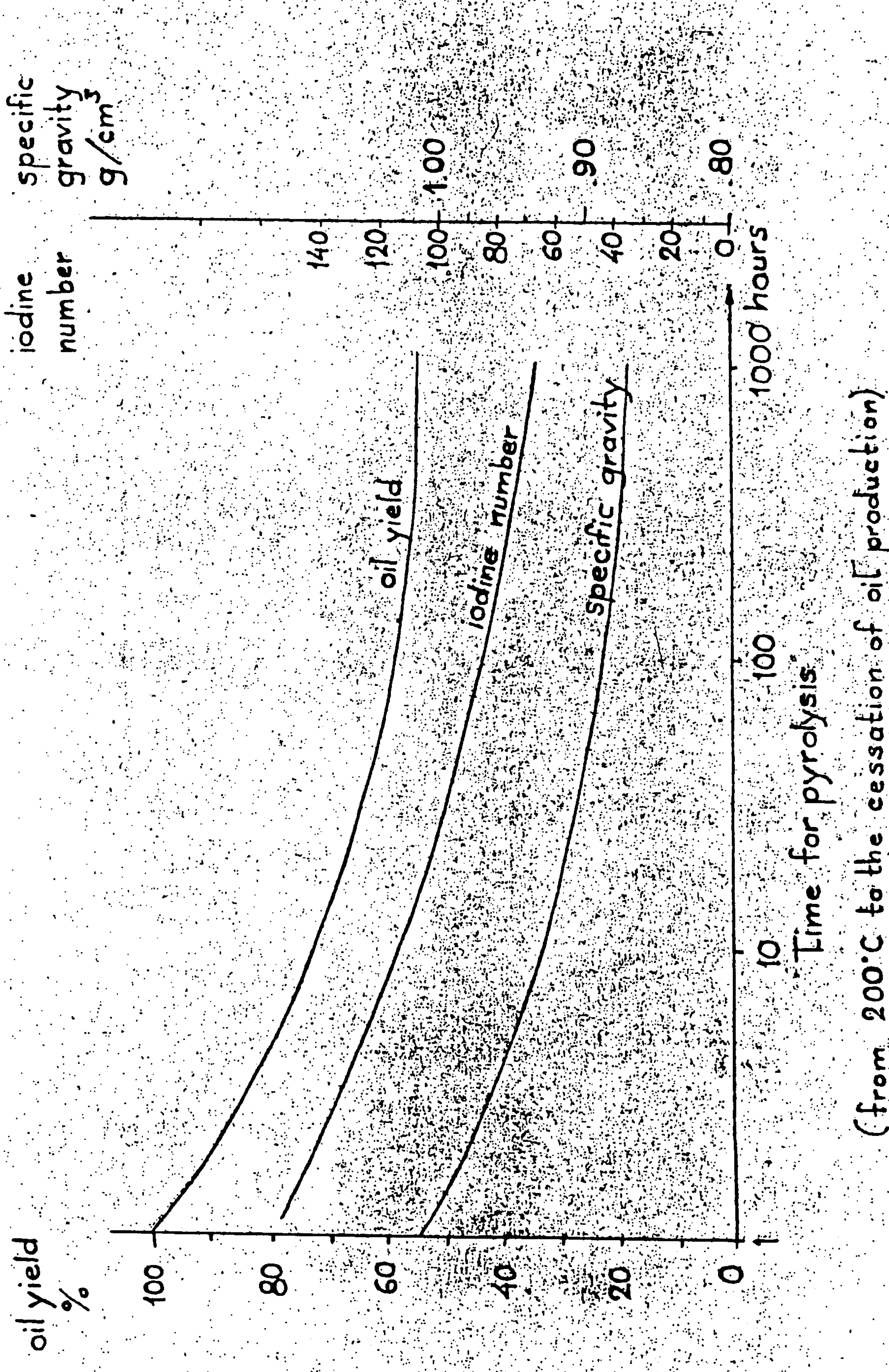
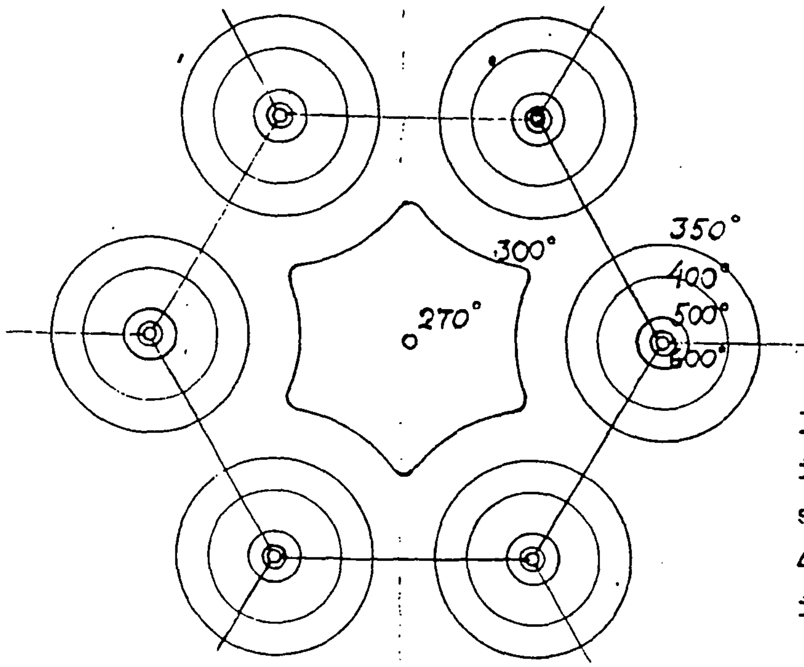


Fig. 2.

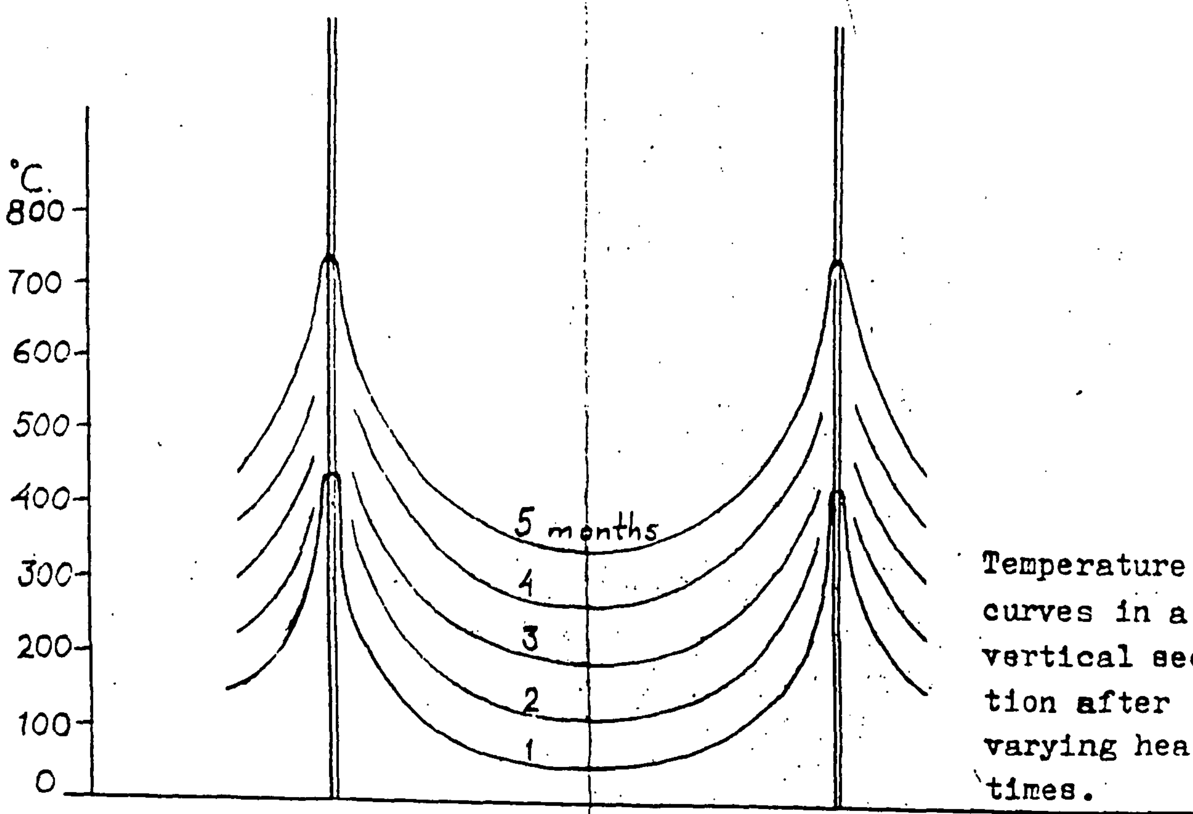
Fig. 2.

SVENSKA SKIFFEROLJE A.-B. Ljungströmsanläggningen	Heat distribution in the shale around the elements. (Approximate curves.)	



Isothermals in a horisontal section after 4 months'heating.

Fig. 3.



Temperature curves in a vertical section after varying heating times.

Fig. 4.

SVENSKA SKIFFEROLJE A.-B.

Ljungströmsanläggningen

The shale deposit and the situation of the oil recovery plants at Kvarntorp, Sweden.

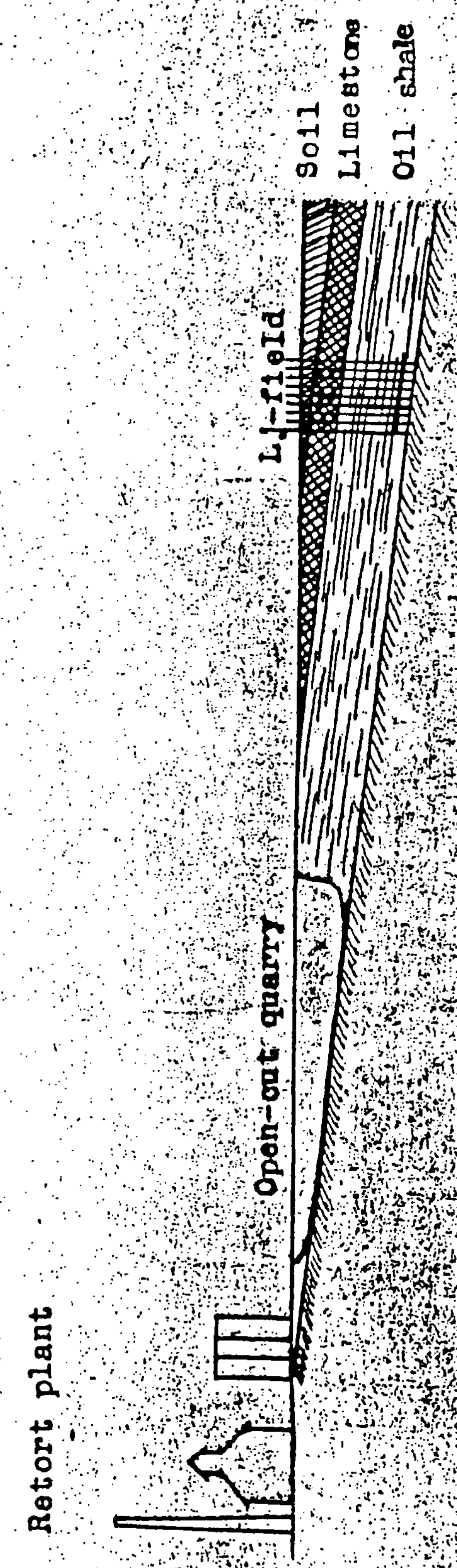


Fig. 5.

SVENSKA SKIFFEROLJE A.-B.

The Ljungström System for shale oil recovery.

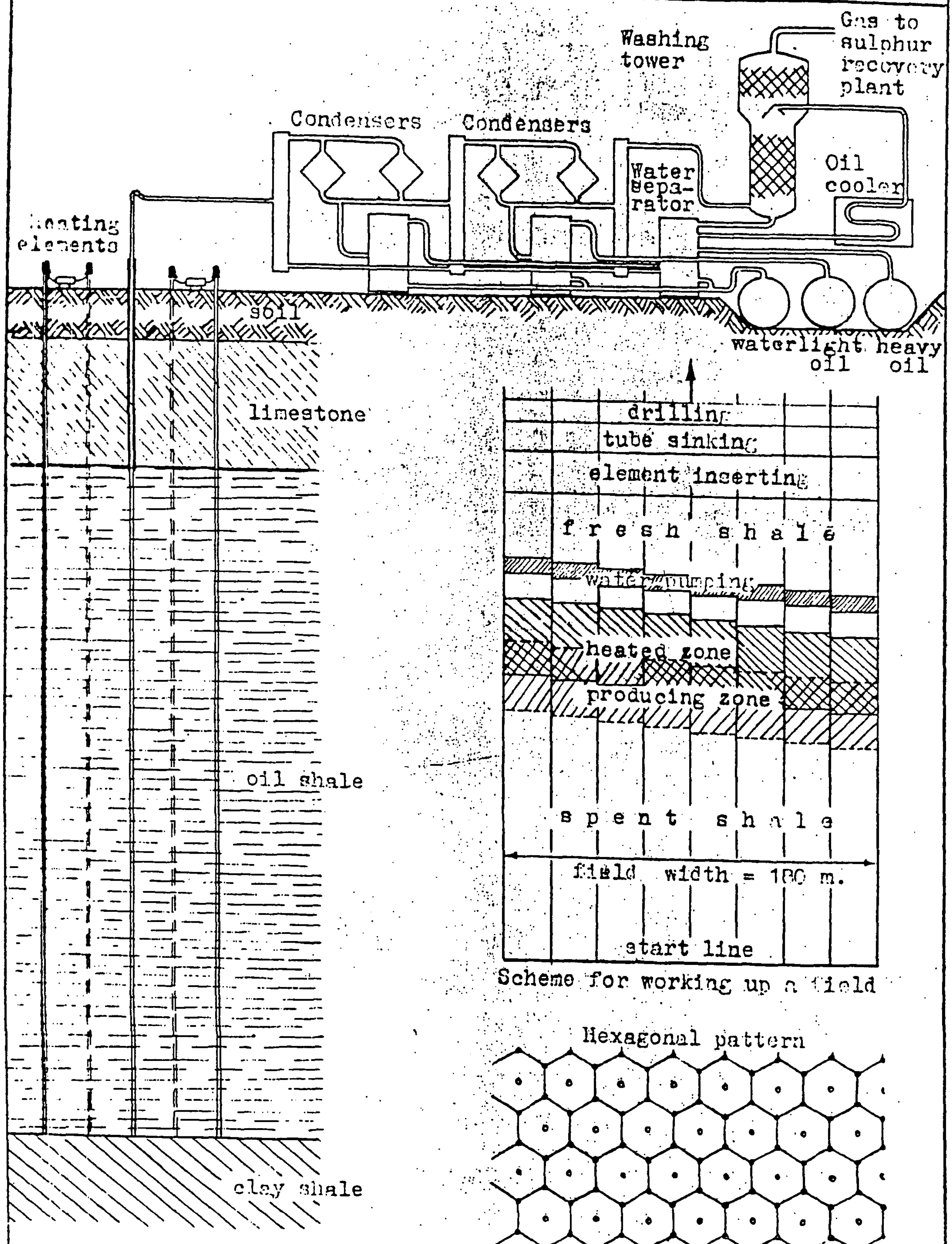


Fig. 6.

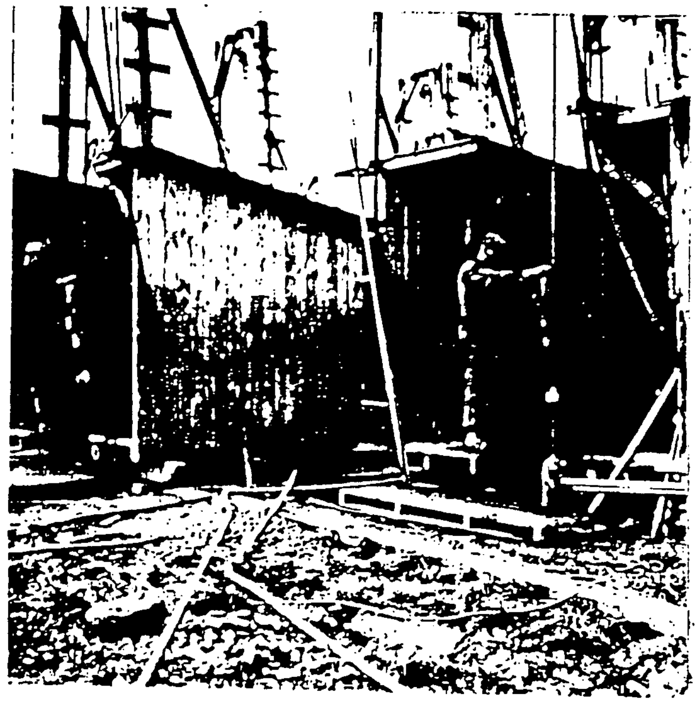


Fig. 7. Drilling.

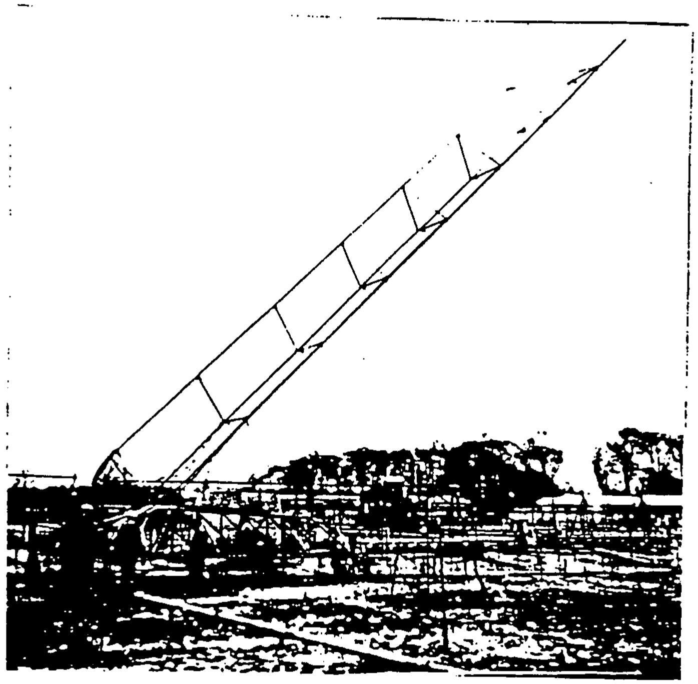


Fig. 8. Tube - sinking.

Fig. 10. Ground water pumps.

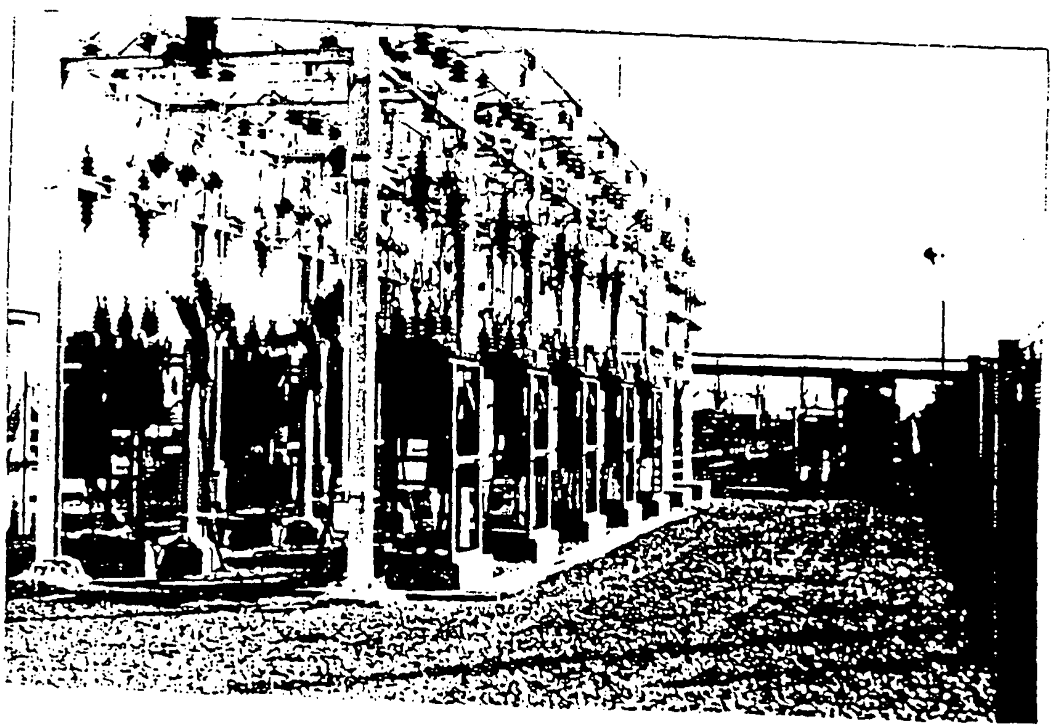


Fig. 11. Distribution and switchboard station.

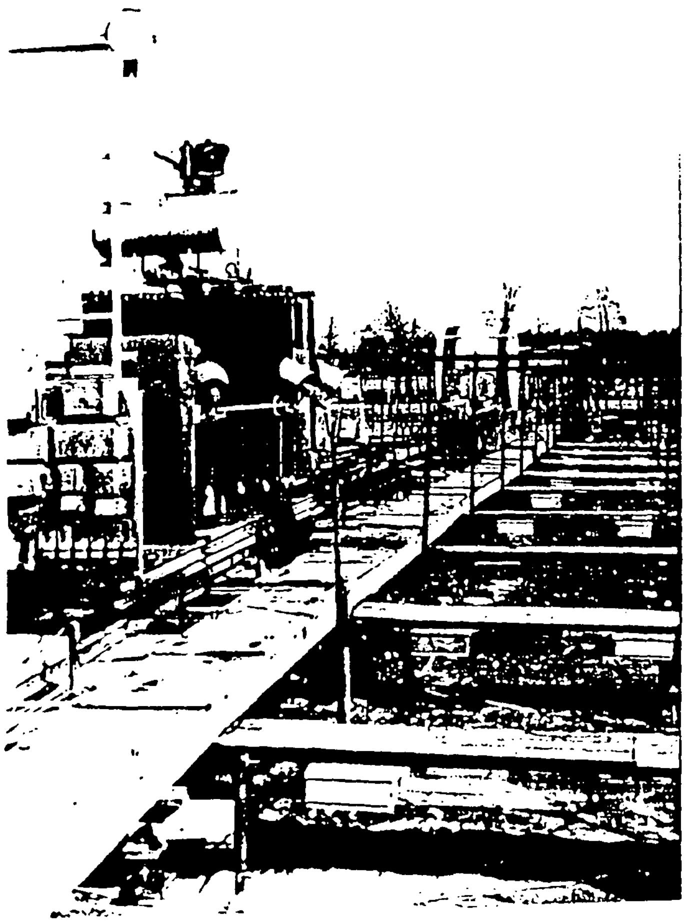


Fig. 12. Field transformers, cable covers, and gas collecting tubes.

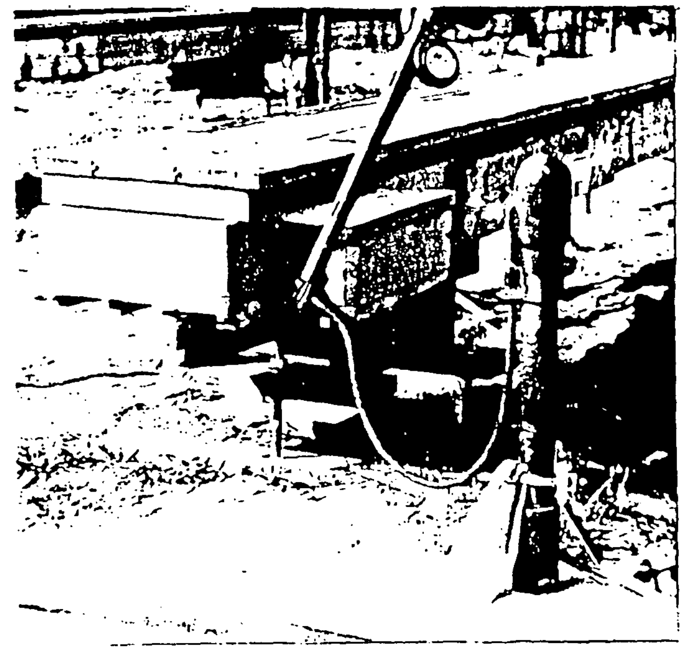


Fig. 13. Element top with cable.

Fig. 14. Condensers.

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Ljungströmsanläggningen

Power consumption
as function of field size

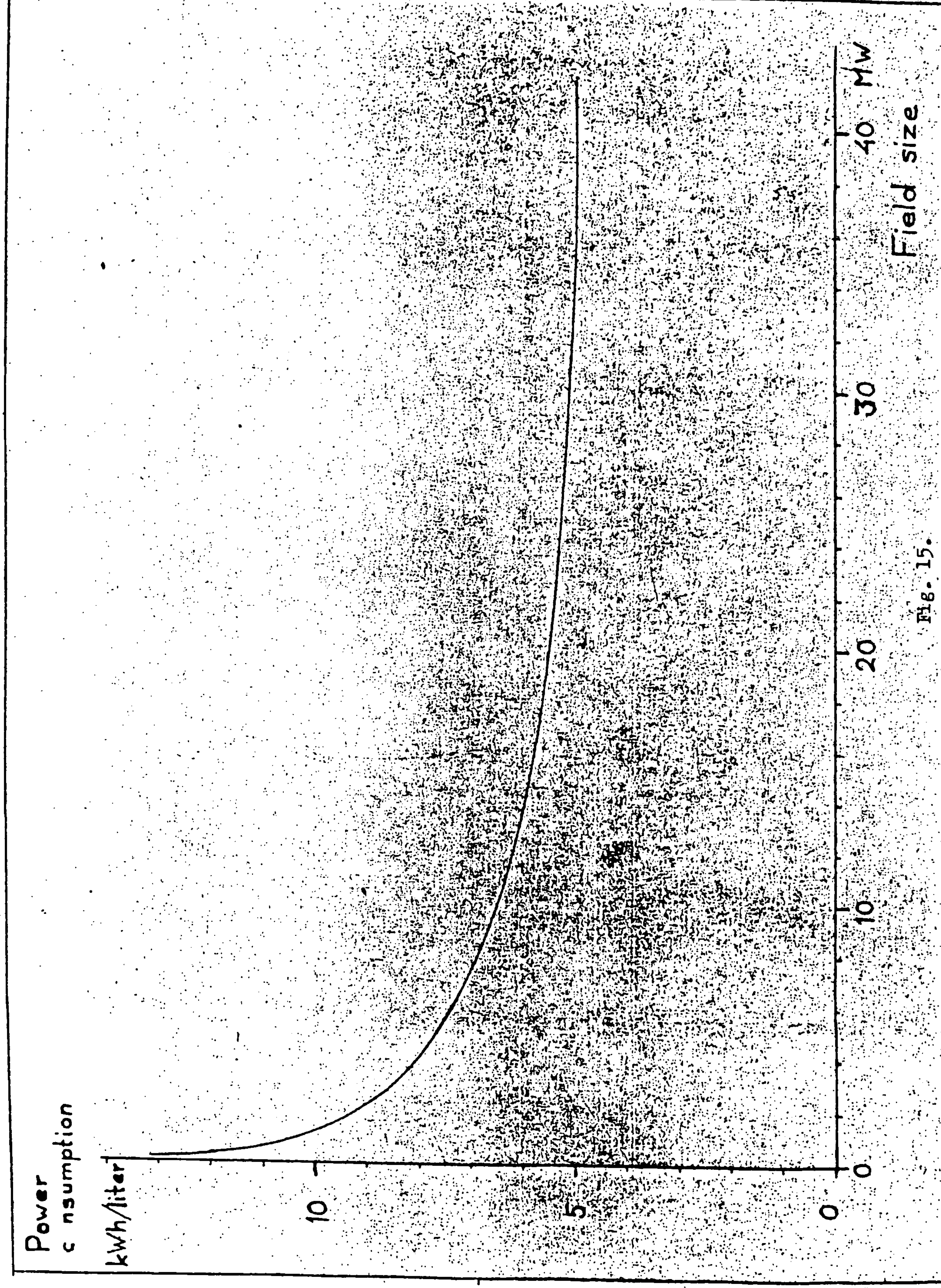

Fig. 15.

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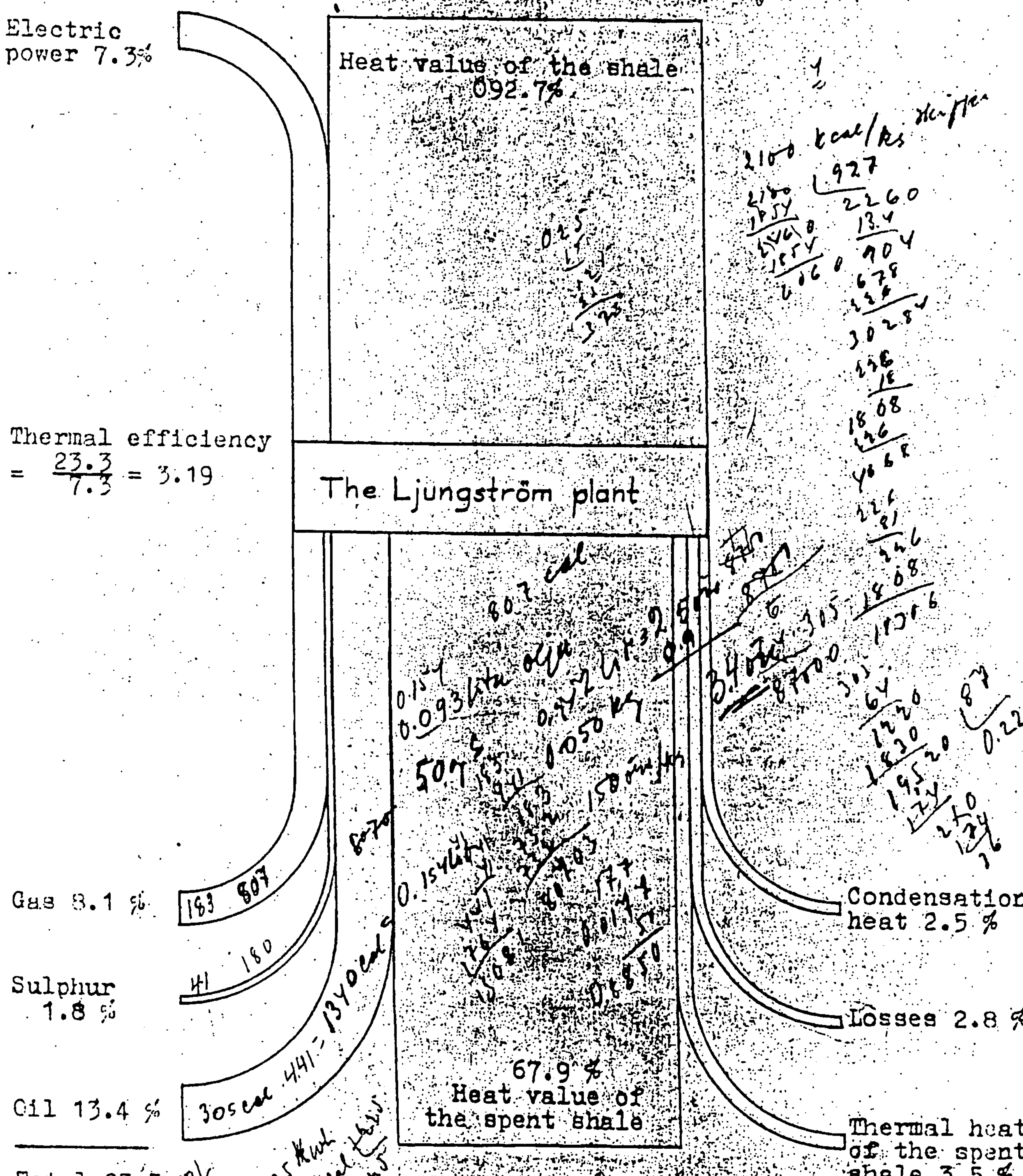
Ljungströmsanläggningen

Energy balance for the Lj-field

Input energy



Output energy

Fig. 16.

Fig. 17. View of the Norrtorp plant.